Divergence in Californian Vegetation and Fire Regimes Induced by Differences in Fire Management across the U.S.-Mexico Boundary

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Introduction

Every year California experiences cycles of disasters produced by wildland fires that result in denudation of hillsides, flash floods, accelerated erosion, and destruction of homes. Modern fire suppression strategy in California and the United States, intended to prevent such disasters, is based on a nineteenth-century view that wildfire is wholly unnatural in ecosystems due to human ignitions. This mindset is popularized in slogans such as "Only you can prevent forest fires." The simplicity of this perspective presupposes man's power over nature. Indeed, no other natural hazard has been more underestimated than wildland fire. This is illustrated in the following word substitution game when Smokey the Bear says: "Only you can prevent earthquakes, only you can prevent volcanic eruptions, or hurricanes" – truly absurd perspectives. In large conflagrations, the energy release exceeds the energy of suppression by many orders of magnitude. Fire control is effective only in putting out very small fires or the very end of large dissipating fires. Society recognizes the power of geologic and atmospheric processes, yet is oblivious to the power of fire.

Evidence indicates that suppression aggravates the threat of wildfire by increasing fire size and levels of intensity that make it impossible to protect property and resources. Yet, the impact of suppression was never seriously questioned for most of the twentieth century because its legacy on ecosystems is one of unintended consequences that emerged slowly and subliminally. Only by 1970 did important debate emerge, after an outbreak of enormous conflagrations throughout southern California, including the 60,000 ha Laguna fire near San Diego.

Fire policy failed to recognize that in this Mediterranean-type climate, fire was a natural part of ecosystem evolution, and periodic fire was necessary for the maintenance of plant communities (Barbour and Minnich, 2000). The natural ecological role of fire is to rapidly oxidize the complex organic molecular structure of wood and foliage into simpler components, while releasing large amounts of heat. Fire is also essential in maintaining nutrient cycles in which organic matter, produced by photosynthesis from simple compounds, is ultimately decomposed and recycled back into simple compounds.

Decomposition is the slow oxidation of plant materials through grazing animals and ultimately by soil microbes and fauna. In California's mediterranean climate, however, decomposition of organic matter proceeds slowly because temperatures are too low for microbial

L. Fernandez and R.T. Carson (eds.), Both Sides of the Border, 385–402.
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activity when moisture is available in winter. Thus, fuel tends to accumulate because the vegetation itself produces more organic matter—dead leaves, branches, and desiccated living material—than is decomposed. Fire becomes inevitable because of ecosystem properties that lead to the conservation of biological mass, in which photosynthesis is balanced by both slow oxidation and rapid oxidation in the form of fire. Although this equation describes a balanced budget, there is typically a time lag between fuel accumulation and burning so that the budget is balanced over longtime scales. How long depends on the ecosystem and management policy.

Today, the role of natural disturbance is widely recognized, and during the past 30 years, there has been a proliferation of research that address significant questions concerning fire regimes (number of fire events, size, intensity, vegetation damage, postfire successions). These include the following: (1) what was the baseline (presuppression) vegetation and fire regime; (2) what would happen without suppression (a corollary); (3) how has suppression altered that baseline; and (4) how can fire management optimize protection of watersheds, property, and resources. However, because suppression has been universally practiced for a century, the quantitative dimension of fire suppression impacts is difficult to study at the landscape scale because no pristine forests in California exist with unmanaged fire cycles to serve as comparative controls. Hence, scientific evidence on the extent to which suppression led to altered ecosystems and anomalous fuel buildup is uncertain to this day. Published reconstructions of past fire regimes and vegetation dynamics in California are usually indirect and involve the interpretation of local evidences that may not capture fire as a spatial process. Without concrete answers to these challenging inquiries, we cannot even address the most pertinent question: How can fire be reintroduced to restore stable ecosystems and ultimately to protect property and resources?

For these reasons, our research group has undertaken several studies in adjoining Baja California, Mexico (BCA) because a presuppression vegetation and fire regime baseline is a modern condition. Grasslands, chaparral, conifer forests, and desertscrub similar to that in Alta California cover northern Baja California (Minnich and Franco-Vizcaíno, 1998). The region□s remoteness has helped to preserve a rural land-use pattern dating back to the Dominican mission period in the late eighteenth century: mostly cultivation of fruit trees and gardens near ranchsteads and transhumance cattle grazing by families rooted in the region□s open-range livestock economy. Isolation has been accompanied by little or no fire control. This enduring traditional land-use system has resulted in a distinctive relationship between humans and nature that is unique within the Californian floristic province.

Societal differences in land management agendas have resulted in a natural experiment that has caused vegetation and fire regimes to diverge to the north and south of the U.S.-Mexico boundary (Minnich and Bahre, 1995). Our research has developed spatial databases to described uncontrolled fire regimes, using time-series aerial photographs from the present back to the 1930s. Vegetation change was also compared with transborder ground surveys. This study compares transborder vegetation and fire regimes in California, using chaparral and mixed conifer forests as examples. We describe vegetation and fire history on the Mexican side for comparison with similar ecosystems on the California side. The focus is on chaparral in cismontane San Diego County in southern California (SCA) and in northern Baja California (BCA) as far south as Ensenada and the conifer forests of the San Bernardino Mountains (SBM) in California and the Sierra San Pedro Mártir (SSPM) 100 km southeast of Ensenada. We then evaluate how management can be optimally applied toward the protection of property and resources in California, as well as changing Mexican fire policy in relation to rapid development in BCA.

The modern landscape

Vegetation maps show that SCA mediterranean ecosystems extend 200 km into BCA (Minnich and Franco, 1998; Barbour and Minnich, 2000). Grasslands, coastal sage scrub, and maritime desertscrub in the coastal valleys and foothills are replaced by chaparral and conifer forests in the higher mountains. Pinyon-juniper woodlands cover leeward escarpments before being replaced at lower elevations by Sonoran Desert scrub. The chaparral consists of a contiguous layer of evergreen sclerophyllous shrubs 1-5 m tall forming extensive carpet-like stands. It covers around 700,000 ha^{-1} on the coastal slopes of the Peninsular Ranges of SCA and BCA. Californian mixed conifer forest, which occupies 14% of California and 100,000 ha in BCA, including 40,000 ha in the SSPM, comprises a diverse mixture of tall coniferous trees including Ponderosa Pine (*Pinus ponderosa*), Jeffrey pine (*P. jeffreyi*), sugar pine (*P. lambertiana*), white fir (*Abies concolor*), and *Calocedrus decurrens* (Barbour and Minnich, 2000).

The climate is mediterranean characterized by winter rain and summer drought. Mean annual precipitation increases from 20-30 cm along the Pacific coast to 50-80 cm in the mountains.

Transborder contrast in fire and vegetation dynamics

The chaparral and mountain pine forest landscape of BCA may seem exotic to those accustomed to similar landscapes in SCA. Almost any afternoon during summer there are a few smokes that can be seen in the distance. Beneath a smoke column is a flame line creeping along a slope. Thunderstorms form almost daily along the mountains, the lightning triggering small fires, most of which burn out in a day or two. The chaparral appears as a diverse, fine-grained patch mosaic, much like that of a quilt. From any view, a dozen patches of different ages are visible—from fresh burns, to medium-statured thickets, to impenetrable old-growth stands. In the highest mountains are extensive open parks of large pines—the subcanopy having only a few young trees and scattered shrubs. Many trees bear large burned-out cavities (catfaces) on their lower boles that were created by ground fires. Recent burns had left skeletons of burned shrubs and tree saplings as large as 10 to 20 m. The old surviving pines display an umbrella-like canopy. By evening the large fires fade in the cooler temperature and rising humidity, but many will reestablish from burning logs and dead trees the next afternoon, and the next—with a few burning for weeks or into the autumn until ultimately doused by winter rains.

North of the international boundary, the mountains support unbroken carpets of dense, old-growth chaparral that are sliced by an occasional fuel break along a ridge, and interspersed with a few extensively denuded watersheds from a recent conflagration. Pine forests are thick with young shade-tolerant firs and cedars, an immense accumulations of ground litter and decomposed logs. The old trees show high levels of mortality from disease and insect attacks. Forests are becoming increasingly fragmented and divided by post-burn patches of oak woodland and timberland chaparral as a result of intense stand-replacement burns.

The sharp transition between the two regimes cannot be explained by natural gradients in flora or weather; it follows the international border. Climatic gradients including temperature and mean annual precipitation cross the border at right angles, and the prevailing winds are everywhere westerly. Without distinctive suppression systems, changes in fire regime should be expressed in a continuum along environmental gradients, and not as the discontinuity seen between the two countries.

Differences in the landscape are seen in the fire history of chaparral in BCA and SCA (Fig. 1). Perhaps the most conspicuous outcome of the transborder experiment is a discrete transformation of chaparral stand configuration—from a fine-grained patch structure in BCA to a coarse patch structure in SCA (Minnich and Chou, 1997). The small size of fires in BCA has been accompanied by high burn densities (about 7 kha^{-1} 50 yr^{-1}), with most burning accomplished by fires less than 3,000 ha. In SCA fire densities are only 1.0 kha 50 yr^{-1}, with most burned area accomplished by a few events over 10,000 ha. Despite these differences, the fire rotation periods in both countries are about the same, about 70 years, i.e. the past century of suppression has not altered the pace of fire disturbance in chaparral at the landscape scale.

In the mixed conifer forest belt at higher elevations, there are large differences in fire return intervals. In the SSPM fires have burned virtually all forests at least once since 1925 with fire intervals averaging twice a century (Minnich et al., 2000). Fire size frequency distributions are similar to those in the chaparral in BCA. In contrast, few mixed conifer forests have burned in California under fire suppression because fires spreading into them from adjoining chaparral and other ecosystems are readily extinguished in the forest. In the SBM, less than 10% of forests have burned since records began in 1910 (Minnich, 1988). Comparable burning rates have occurred in extensive mixed conifer forests of the Sierra Nevada (SNEP, 1996).

How patch mosaics work

An important aspect in developing fire disturbance theory to explain the divergence in fire history in SCA and BCA is choosing an incontrovertible starting point that leads in directions productive for research. The model in Minnich and Chou (1997) is based on the fact that fire requires fuel; this reveals that the *cause* of fire is fuel energy accumulation in vegetation (chemical energy) by fixing CO_2 into carbohydrate. Fire occurrence in chaparral is time-dependent as a result of cumulative fuel buildup. How stored energy in chaparral is released reflects primarily vegetation growth, structure, and cumulative fuel buildup, and secondarily weather and terrain. This new starting point requires a reversal from the standard perception of fire in the following axiom: During the passage of a flame line, *vegetation is not burned by fire; it burns itself by releasing stored photosynthetic energy.* The focus on ignitions in the initiation of fire is akin to the tail wagging the dog. Ignitions are ubiquitous and most fail to establish fires because they are too abundant relative to slow fuel accumulation rates (Minnich et al., 1993; Minnich and Chou, 1997).

This cross-border difference is explained by a time lag that exists between fuel accumulation burning, making fire self-limiting, and thereby time-dependent (Minnich and Chou, 1997). Fire occurrence is constrained in space and time by the rate of fuel accumulation in previous fire history. Chaparral brings low fire hazard during the first years after fire because it has low combustible biomass. Fire hazard increases with time, resulting in a variable fire hazard from stand to stand, depending upon their age. As a result, fires preferentially burn old stands (more than 40-50 years old), the younger stands constraining the progress of burns. As a result, mosaics of fire-created patches assume a self-organizing spatial process where the occurrence of fires is influenced by previous fire history, and also affects fires at some later stage. In BCA, numerous small to medium-size fires (mostly less than 5,000 acres) create a heterogeneous fragmented patch structure that resists the development of large fires. In SCA, initial attack suppression reduces the number of medium-size fires, resulting in a coarse patch structure that encourages large fires, some as large as 20,000 to 60,000 ha. Fire intervals in both countries are similar, about twice a century. The similarity of fire return intervals in SCA and BCA supports

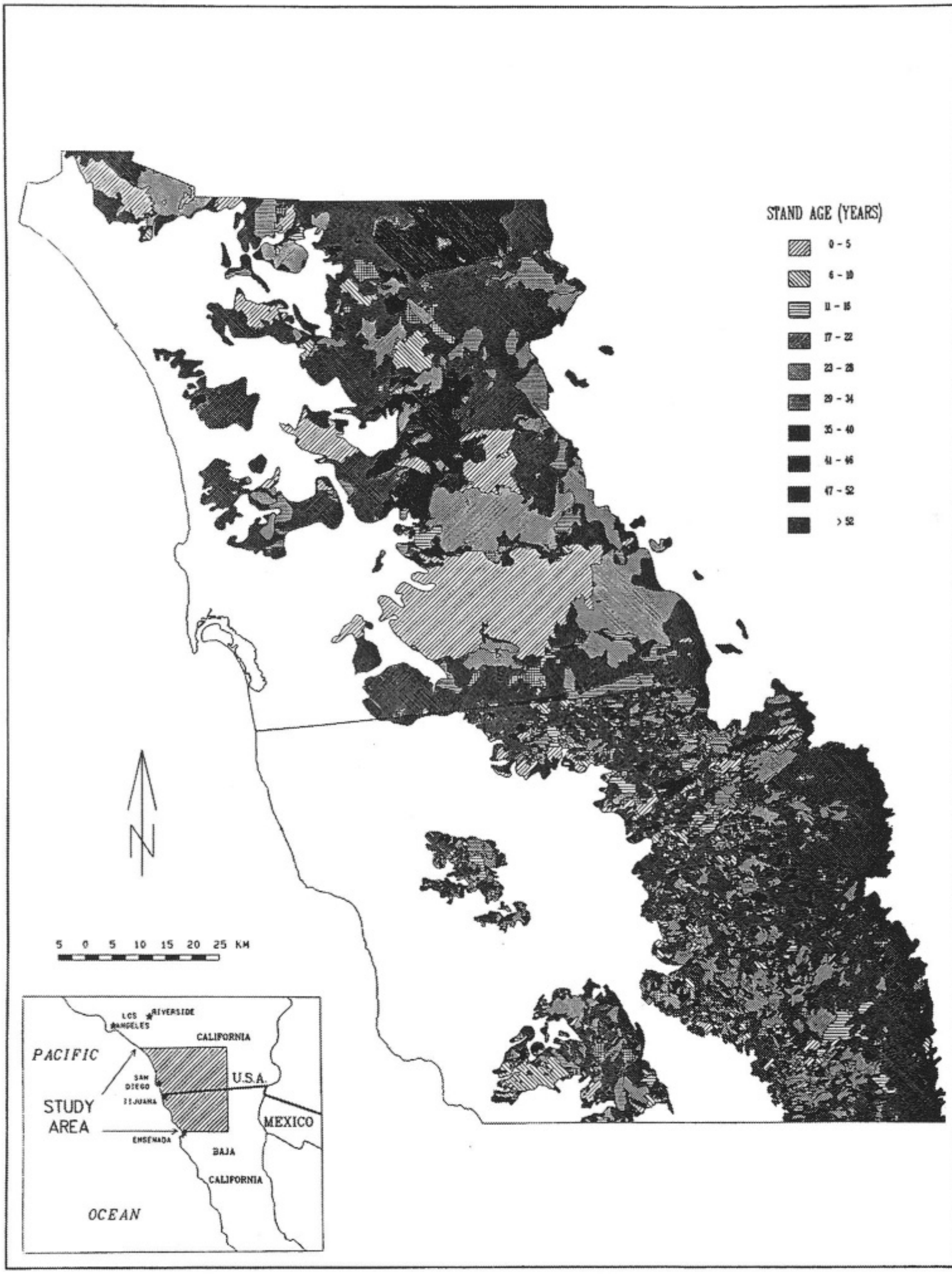

Figure 1. Chaparral patch mosaic (time-since-fire) in 1971.
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the argument that the chaparral productivity (i.e. fuel supply) dictates landscape-scale rates of burning, with a negative feedback between fire frequency and fire size.

The time-dependence in fire occurrence is related to the fact that fires can propagate through chaparral or forests only if the heat released in burning fuel exceeds the energy heat sink of water in vegetation. Factors contributing to increasing fire hazard during succession are fuel continuity (stand cover), total biomass, and lowering of stand fuel moisture from increasing dead-to-live stand fuel ratios (Rundel, 1983; Keeley and Keeley, 1989; Barro and Conard, 1991). Fire hazard in stands is low during the first decades of succession because chaparral canopy is initially discontinuous for around 10 years, and stand fuel moisture is high due to leaf stomatal controls that regulate transpiration under high evaporative demand to levels above combustion thresholds. The accumulation of flammable dead fuels gradually increases with time-since-fire, especially after 30 years spring (summary data in Rundel, 1983) due to the reduced ability of shrubs to meet concurrent demands of photosynthate storage and growth (Sparks et al., 1993). Another model is that the expanding foliage area of dominant shrubs in maturing stands advances seasonal soil drying, hastening the onset of seasonal drought stress (Riggan et al., 1988).

Self-organized turnover of patch mosaics also occurs in mixed conifer forests of the SSPM. It is hypothesized that fire hazard also increases gradually with cumulative buildup of needle litter, shrubs, and conifer recruitment (Minnich et al., 2000).

Individual fires, of course, each have different sizes, intensities, and severity in vegetation damage because each was associated with a unique combination of weather, terrain, and fuel conditions. However, the cumulative impact of all fires scaling at centuries or millennia results in spatial structures arising from time-averaged processes on the landscape that are equilibrated to ecosystem productivity (landscape fuel buildup) tied to climate. As long as fire occurrence is spatially and temporally random, regional burning properties will concentrate on the modal properties of fire factors.

Fire control has a significant effect on the weather of fires because the suppression of small fires nonrandomize the occurrence of large fires (Minnich and Chou, 1997; Minnich, 1983). Relatively small changes in relative humidity and wind spreads may produce large differences in energy release associated with spread rates of flame fronts (fuel energy consumed per time). On an area-weighted basis, fires in BCA establish by chance during prevailing onshore sea breezes and slope winds in summer (relative humidity 20-40%, winds 5-20 mph). In SCA, the efficient elimination of countless small fires is a selective process that nonrandomly encourages very large "escaped" burns to coincide with severe weather (fires starts are easily extinguished in "normal" weather), resulting in high average spread rates and flame line intensities. Most burning in SCA coincides with offshore Santa Ana winds in autumn (relative humidity 10-20%, winds 20-50 mph). The corresponding denudation of younger stands increases fire size and homogenization of the mosaic.

Historical roots to the U.S. and Mexican fire management systems

The United States and Mexico form one of the most profound political boundaries in the world, dividing respectively, an industrialized, urbanized economy on the U.S. side from a "third-world" developing economy on the Mexican side. Yet, the transborder region began with the same political and ecological baseline. BCA and SCA were first settled by Franciscan missionaries in response to directives by the Spanish crown to expand the Spanish sphere of influence in the Californias against Russian encroachment (Bolton, 1927). In 1769, the

Franciscans initiated an unbroken chain of missions that eventually developed an extensive open-range grazing economy and local agriculture in the coastal plains, a land-use system that persisted through the Hispanic period to the mid-nineteenth century. The mountains were avoided except for occasional harvest of timber and for use as summer pasture. The division of California from Baja California ultimately originates from an agreement made at the beginning of the mission period. Once established in Alta California, the Franciscans quickly realized that they had insufficient manpower to establish missions south of San Diego and, furthermore, Dominican leaders desired a share of California. In 1772, a "concordat" was signed between the viceroy of Mexico and the leaders of the Dominican and Franciscan orders. The Dominicans agreed to take charge of the old Jesuit mission system in Baja California and to develop missions in the mediterranean lands of the northern peninsula as far as San Diego. The Franciscans had jurisdiction of Alta California from the present international border northward (Meigs, 1935). Lands originally in Franciscan holdings came under control of the United States in 1850; Dominican lands remained in Mexico.

Until recently, most of Baja California's biological environment was not as intensively exploited as Alta California, nor were its wildlands under formal protection. Indeed, the vegetation, protected by isolation, has a pristine character rarely seen in Alta California. Until the end of World War II, northern Baja California remained largely politically and economically isolated and undeveloped, despite its proximity to the rapidly expanding economy of Alta California (Henderson, 1964). Within Mexico, Baja California was a distant outpost from Mexico City.

The region□s isolation has been responsible for a centuries-long delay in the development of agriculture and ranching after the Spanish discovery of the peninsula (Henderson, 1964). In the late eighteenth century, the Dominican padres conducted many enterprises with indigenous farmers and ranchers, but these efforts resulted in localized subsistence agriculture and little immigration into northern Baja California.

Cattle grazing remained the most significant economic activity through most of the nineteenth century. As the mission system disappeared, Dominican landholdings were granted or sold to local citizens, usually Mexican government officials and military officers, who began subsistence cattle ranching in the sierra. The gold strikes in the Sierra Juárez and the west slope of the Sierra San Pedro Mártir between 1873 and 1890 resulted in increases of cattle and commercialization of cattle operations, but the ores played out within a few years and the miners dispersed (Henderson, 1964; Chaput et al., 1992). Except around the Dominican missions, agriculture did not exist in these semi-arid lands until the 1880s. The population increased with the expansion of agriculture during the dictatorship of Porfirio Díaz in 1877-1911 (Henderson, 1964). During this period, much of the best land for agriculture, mostly grassland in the coastal valleys and desertscrub on the Colorado Delta, was cleared for crops. Dry farming of wheat and barley was successful in Valle Ojos Negros, in Valle San Vicente, and in the basins southeast of Tijuana. The inaccessibility of the pine forests has prevented significant removal of timber during the past two centuries.

The total population of the entire peninsula of Baja California, which covers an area nearly equal to that of Alta California, was counted in the thousands into the early twentieth century (Henderson, 1964). Today Baja California is mostly an unfragmented, wild landscape, with scattered patches of agriculture, reminiscent of the California landscape in the nineteenth century. Most mountain lands are effectively unoccupied other than for a few scattered, small ranches. Wildland fires in the mountains are uncontrolled to this day, and deliberate burning is

still practiced by *vaqueros* and farmers. Large parts of the landscape remain little altered from the late eighteenth century, when Europeans first described them (Minnich and Franco-Vizcaíno, 1998).

In contrast, Alta California's ecosystems underwent a cycle of intense human exploitation parallel to that in many other areas of the western United States (Lockmann, 1981). The Gold Rush in 1849 drew large numbers of Anglo-Americans to Alta California, and when the mines were exhausted, the well-watered lands permitted a transition to agriculture. Forests were logged for construction, fuelwood was culled for mining operations and domestic use, and rangelands were grazed by livestock. By the end of the century, after forests and rangelands had been exploited across the United States (Robinson, 1975), a growing awareness of the need to conserve those areas arose. Public concern for a variety of issues including watershed protection, wildfire control, and forest protection resulted in large areas of the public domain being placed into national parks and national forests. Logging and grazing were managed or prohibited; fire control was instituted.

A Mexican fire regime in California

Fire history evidence in California suggests that a BCA fire regime had evolved into the modern conflagration regime during the early twentieth century (Minnich, 1987; Minnich, 1988). These writings suggest that small fires and patchiness were characteristic of chaparral during the late nineteenth century. According to Mendenhall (1930), an early forest ranger in the San Gabriel Mountains north of Los Angeles, "Fires occurred every year...and were not extensive due to the fact that they ran into older burns and checked themselves." In the San Bernardino Mountains, the 1903-04 L.C. Miller Silvicultural Survey party saw evidence of fire at ten localities across an area of about 20,000 ha. During the U.S.-Mexican boundary survey of the 1890s, which encompassed the coast ranges between Mexico and the San Jacinto Reserve, boundary workers stated that "the signs of fire having gone through the brush are constantly evident." John Leiberg, who conducted the forest reserve surveys under the U.S. Geological Survey at the turn of the century, noted that in the San Gabriel Reserve, recent fires burned over 12,000 acres in four widely separated drainages (Leiberg, 1899, 1900). Leiberg made the most explicit account of patch mosaics in the San Jacinto Mountains, 100 km east of Los Angeles, describing the chaparral as "a growth which varies from extremely dense to thin or open, but rarely forms large uninterrupted patches. The dense portions are commonly separated by narrow lanes [burns], which are wholly free of brush...." He also stated that "recent fires...[were] scattered throughout the reserve in small tracts." Tree-ring fire-scar data reveal evidence of periodic fire in mixed conifer forests throughout California (McBride and Laven, 1976; Kilgore and Taylor, 1979; Swetnam, 1991, 1993). Newspaper accounts describe several extensive subcanopy fires in the logging belt of the western San Bernardino Mountains between 1860 and 1900 (Minnich, 1988). Ground photographs dating to the late nineteenth century reveal open park-like forests and basal fire injury to tree boles (Leiberg, 1899, 1900).

After 1900, most lands on the SCA side were placed into the Cleveland National Forest, and Cuyumaca and Anza-Borrego State Parks. Remaining lands were used for cattle grazing in herbaceous communities under fence. Suppression has been official policy since 1900 (Lockmann, 1981; Pyne, 1982; Minnich, 1987a). In California, organized fire suppression developed from a concern for watershed protection, flood cycles, erosion, and damage to property. This practice dates to around 1900 when a national consensus emerged toward conservation of forest resources. In 1900, Gifford Pinchot, Chief Forester, visited Pasadena to

"press hard for the employment of 100 rangers [to be] employed seven months/year cutting [fuel] breaks on the ridges, clearing out undergrowth, and building trails through the mountains so that every section can be reached readily by fire fighters. The rangers could patrol their ranger district ... [to] keep a lookout for blazes" (Minnich, 1987). The fuel breaks were designed to break up chaparral into blocks in order to contain fires within individual stream drainages. The "10 o'clock policy" implemented at this time, i.e. that all fires be put out by 10 o'clock the next morning, has been practiced ever since with ever increasing technological assistance, primarily for the suppression of large fires. The most important change was the introduction of aerial drops of water or chemical retardants beginning around 1950. Also utilized are bulldozers and massive manpower, brought in from many areas outside California to build lines around the fire perimeter, utilizing the fuel break systems. The expansion of large cities in SCA since World War II has resulted in an ever increasing urban/wildland interface.

When did suppression begin altering chaparral fire regime?

Keeley et al. (1999) present data that fires in California "brushlands" have always been large since fire records began in the early twentieth century. They propose that (1) because the size of fires in SCA have remained unchanged since records began in 1910, and (2) because suppression became effective with technological advancements in 1950, then fires have always been large, even before suppression. This argument rests on an unsubstantiated *ad hoc* assumption that the effectiveness of suppression is coupled with technology. While small fires can be suppressed with relatively primitive means, suppression of very large fires has never been effective. The spatial extent of fires does not decrease with increased funding of suppression nor with improvements in technology. Despite vast differences in funding and technology, fires have been larger in California than in Baja California since the 1950s. Moreover, the discontinuity in patch density and size along the international border had already developed by the 1920s (Minnich and Chou, 1997). The most expensive aspect of suppression—encircling large fires—is futile because the energy release of flame lines exceeds the energy of suppression by orders of magnitude. Large fires easily skip over fuel breaks because passing embers in the wind initiate new flame lines kilometers in advance of the primary flame line. Suppression is effective only during low energy states, i.e. the extinguishing of small fire starts, a process that began in earnest by 1900 (Minnich, 1987). This can be done at little cost and with little technology.

Evidence that chaparral patch dynamics were altered soon after the initiation of suppression is illustrated in the San Gabriel Mountains where chaparral covers 150,000 ha (Minnich, 1987). Immediate suppression of small fires proved to be quite effective. After two successful seasons, the October 27, 1902 edition of the *Los Angeles Times* reported in an interview with T.P. Lukens: "The local rangers have been very fortunate in nipping blazes in the bud this season. No disastrous fires have occurred..." From 1905 to 1918 forest rangers combed the hills to extinguish small fires. A list of fires compiled by Mendenhall (1930) reveals remarkably little burning from 1905 to 1918 with the total burn area of only 8500 ha, or 5.6% of the chaparral which covers around 150,000 ha. For the 14-year period, the area of chaparral burned per year averaged 0.4% instead of long-term rates of 2.0%. These trends show that the mean age of chaparral stands increased throughout the mountains during this period. The hiatus was followed by three massive conflagrations totaling 80,000 ha in 1919 and 1924. The presuppression patch mosaic described in the late nineteenth century was already altered in 20 years.

The processes leading toward the enlargement of patch mosaics were understood even during this period. William Mulholland, better known for his efforts in importing Owens Valley water to Los Angeles, deduced a change in the pattern of fire at the turn of the century, and explained it in terms of pre-existing patch mosaics (Minnich, 1987). In an interview with the *Los Angeles Times* after a fire in 1908, he stated: “If the portion of watershed burns off each year, then there is always a large majority of watershed covered with a new green growth that will defy any fire. Experience has taught us that we cannot prevent fire. It is better to have a fire every year, which burns off a small area... than to have a big one denuding the whole watershed at once.” Eleven years later, two simultaneous conflagrations denuded 110,000 acres in the San Gabriel Mountains, after which Mulholland stated to the *Los Angeles Times*: “The deplorable thing about the present fires is the vast extent of the territory burned over in a single season. Fires we have every year, but only small areas have been generally burned over at a time and very rarely does it occur that the growth on a watershed is of such maturity as to burn out with a single occurrence.”

Changes in mixed conifer forest

As was the case with chaparral, an early onset of suppression is also recorded in mixed conifer forest. Tree-ring studies show a falloff in burning by 1900 in California (Swetnam, 1993). In contrast to chaparral where fire intervals and species composition have been stable from presuppression to suppression times, the large transnational divergence in fire intervals in mixed conifer forests had led to important differences in species composition and stand structure on both sides of the international boundary. In the SSPM (Minnich et al., 2000), forests consist of open stands of large mature trees dominated by pines, with overstory densities of 65-145 stems ha^{-1} and cover of 25-45%. Pole-size stems in the subcanopy average 15 ha^{-1}. It was hypothesized that the open stand structure resulted from vigorous selective elimination of subcanopy trees by intense understory fires. While chronosequence data show gradual recruitment of saplings to pole-size status over a fire cycle of 50 years, most subcanopy trees perish in landscape-scale fires, leaving only a few to join the canopy layer. The rate of entry into the overstory class is balanced by low overstory mortality rates. Present-day forest densities may reflect a long-term stable forest population structure. Time-series aerial photographs since 1956 reveal that local post-fire recruitment and stand-thickening are balanced by subcanopy mortality of young trees in other stands (Minnich et al., 2000). Estimates of stem densities, stem diameters, and species composition in a timber survey conducted in 1888 are remarkably similar to present stands (Minnich and Franco, 1998).

On the U.S. side, open park-like forests of old-growth trees, similar to present-day forests in BCA, were described and photographed in many areas of California in the late nineteenth century (SNEP, 1996; McKelvey and Johnston, 1992; Minnich, 1988; Vankat, 1977; Vankat and Major, 1978). Forest densities (trees with diameters greater than 10 cm) averaged 80 to 200 ha^{-1}, with most trees having diameters greater than 60-100 cm (Vankat, 1977; Vankat and Major, 1978; Minnich et al., 1995). The decline in burning on the U.S. side after 1900 has been paralleled by stand-densification, and regionwide buildup of subcanopy fuels. Most forests show an age-specific trend away from dominance by Ponderosa and Jeffrey pine, and toward dominance by sapling and mid-size classes of white fir and incense cedar (Weatherspoon et al., 1992; Minnich et al., 1995; SNEP Science Team, 1996; Roy and Vankat, 1999). Older trees show high levels of mortality from disease and insect attacks. The enormous fuel loads in the dense forests of California are encouraging a new pattern of “stand-replacement” or “crown” fires that destroy whole forests. Replicates of Vegetation Type Map Survey (VTM) field quadrats taken during

1929-34 in the SBM show stem density increases of 100-200 stems ha^{-1} (diameters greater than 10 cm) over the past 60 years, with thickening rates directly proportional to mean annual precipitation (Minnich et al., 1995). The density of young stems (diameters smaller than 30 cm) currently range from 50-100 ha^{-1} in the SBM compared to 15-40 ha^{-1} in the SSPM (Fig. 10). The total density of ponderosa pine stands regenerating from the nineteenth century logging in the SBM often exceeded 500 stems ha^{-1} (Albright, 1998). Stand-thickening has led to increasing densities of dead trees related to infestations of bark beetles and pathogens (Pronos et al., 1999). High subcanopy tree mortality in this range was ascribed to competition for light and soil moisture (McBride and Laven, 1999). Both California and SSPM forests experienced drought during 1987-1990, but recent mortality was an order of magnitude less in the SSPM than California, only 1-3 ha^{-1} (Minnich et al., 2000). It was concluded that the effect of the drought on forest mortality rates was offset by low tree densities, reducing competition for soil moisture and nutrients (Minnich et al., 1995, 2000). In the Sierra Nevada, tree densities (stems larger than 10 cm dbh) have climbed to 500 ha^{-1} on west slope ponderosa pine forest (Vankat, 1977; Vankat and Major, 1978; Roy and Vankat, 1999).

Fire Management

Both the large and intense fire represents the least desirable outcome in the management of fire-prone ecosystems because the size and energy release of fires is directly related to the threat of burning, erosion, sedimentation, and flooding of property and infrastructure. The cost of large fires can be enormous. In Los Angeles, California, intense brushfires with 30-50 m flame lines—pushed through thick mountain chaparral brushfields by strong, dry Santa Ana winds from the desert—spread into several suburbs at the urban-wildland interface during the autumn of 1993. These fires easily overwhelmed suppression forces and destroyed about 1,000 homes at a cost of one billion dollars. In 1991, the Oakland fire burned 3,500 homes at a cost of 3.5 billion dollars. Such disasters have occurred repeatedly in California, and each is followed by renewed debate as to whether fire suppression management practiced for nearly a century has contributed to large fires in the state.

The beginnings of fire suppression were a response to threats on land-use and to watersheds. However, this approach is futile if only catastrophic and indefensible wind-blown fires are carried through unmanaged fuels beyond the interface. Sooner or later under orthodox suppression, every house along the interface will be subject to a fire that cannot be fought. The concept that surrounding burns can prevent the destruction of infrastructure is illogical because suppression forces cannot control large fires. This was understood at the beginning of the fire suppression era. William Mulholland stated in 1908, "Experience has taught us that we cannot prevent fire [as]....it is almost impossible to combat mountain brushfires when once they have well started...." (Minnich, 1987).

Fire management is ultimately fuel management. The long-term spatial and temporal predictability of fire can be used as a central concept for effective management in chaparral. Large uncontrollable fires can be mitigated by reintroducing a fine-grained patch mosaic through proactive broadcast burns. Fire poses a cyclical threat in space and time due to the self-regulating property of fire and fuel dynamics, i.e. the removal of fuels in a burn precludes a recurrence for decades. Increasing the number of fires will produce smaller fires but not an increase in the area burned. Fire fighting personnel need only to check the progress of the fire relative to the patch mosaic. This strategy can be accomplished by recycling chaparral at intervals of 30-50 years, depending on local productivity rates. This requirement is actually modest. For example, the San

Gabriel Mountains of California are covered by approximately 150,000 hectares of chaparral. To completely recycle the entire ecosystem at 40-year fire return intervals requires the burning of approximately 4,000 ha each year. This is equivalent to only 2 or 3 burns.

Post-fire chronosequences on both sides of the U.S.-Mexico border show that chaparral is stable under both suppression and uncontrolled fire regimes. Chaparral is stable because sprouting habits and latent seed pools permit efficient stand establishment under short and long fire intervals (Keeley, 1989; Minnich and Bahre, 1995). Chaparral recovery is insensitive to the size of fires because recolonization of burns by long range seed dispersal is not required for any shrub species.

Hence, management strategies can assume that long-term primary productivity rates and fuel production are nearly constant, reflecting the broad-scale climate. Therefore, the spatial extent of burning will approach steady states averaged at the scale of the landscape. In addition, transborder fire history shows that the rates of burning in southern California and Mexico are very similar. Hence, suppression has not resulted in excessive regional fuel buildup, except in the size of patches. It is thus unnecessary to increase the rates of burning to prevent regional fuel buildup. In fact, chaparral cannot be burned at higher rates because the availability of fuels becomes more limiting (an increase in the area of nonflammable vegetation). Without fire control in BCA, high fire densities and fine-grained patch mosaics are a spontaneous outcome due to high natural ignition rates. Hence, broadcast mosaic burning will become a low-maintenance inexpensive management option once a fine-grained patch mosaic is reestablished. To design specific management plans, National Forests and other land management agencies already have fire history databases to reconstruct current patch structure.

Prescribed broadcast burns should be conducted during the summer, which is the primary fire season in BCA. During that time, the weather is fairly constant, being dominated by slope winds moving up the mountain in daylight and down slope at night. Most fires spread with prevailing winds from west to east. Unexpected weather conditions due to the jet stream (such as Santa Ana winds) are practically nonexistent, especially in July and August. Our observations of past fires in BCA have shown that flames normally spread slowly uphill during the afternoon, when daily temperature maxima and relative humidity minima occur. Flames generally stop during the night, with fires persisting in logs and snags.

Other advantages of planned broadcast mosaic burning include the proactive selection of appropriate weather and the forewarning of landholders weeks in advance. The fine grained fragmentation of denuded lands helps to attenuate post-fire sediment yields in watersheds. Fine-grained patch mosaics are also beneficial to biological diversity by enhancing local variability in vegetation successions.

The primary advantage of prescribed broadcast mosaic burning is that large units of vegetation can be burned economically, and over long timescales at rates equal to regional fuel production. However, the current funding system is not suited to planning. Fire management agencies are paid for fire fighting costs *a posteriori* from emergency funds. Little funding is provided up front in budgets for proactive fuel management of the landscape.

Fire management and Land Use

Emergency funding of suppression and FEMA funding of natural disasters encourage land development and rebuilding after fire disasters in dangerous environments at the urban-wildland interface (Davis, 1998). Regional fire management options have also become complicated and intractable with the growth of dispersed, small landholdings within wildlands.

Instead of encircling fires, an alternative policy is to treat settlement inholdings (ranchsteads, villages, camping facilities) as point features, around which fires can be allowed to pass through in a vast periodically flammable landscape. For this strategy to work, there must be intense fuel management around local inholdings. In BCA, local ranches use livestock to remove fuels around buildings. Agricultural zones and cities utilize livestock, or plow fields in contact with natural vegetation. Similar measures can be undertaken in California, including severe building codes that require the design of fireproof structures.

Some scientists and land managers advocate the focus of controlled burns at urban-wildland interface (Keeley, 1999). Clearly, the protection of structures near wildlands should have highest priority. However, this approach is futile if only catastrophic and indefensible wind-blown fires are carried through unmanaged fuels beyond the interface.

Mixed conifer forest

Because few forests have burned in the past 100 years, indefensible stand-replacement fires will be the wave of the future in mixed conifer forest (Albright, 1998). Urbanization within forests has created a fire management dilemma. Fire suppression combined has encouraged stand-thickening and risk of stand-replacement fires. Private lands, many in historic logging areas that have the densest forests, have become urbanized where construction practices utilize wood products for roofs, siding, and decks that add to fuel loads. The presence of people and structures leads to a feedback in which increased need for fire protection further contributes to stand-thickening and buildup of fuels.

Fire managers need to assess fire hazard conditions and develop fuel management strategies as a scale that promotes sustainable ecosystem management and meets fire protection needs. While the presence of structures precludes the use of prescribed fire, mechanical treatments can be used to mimic the effects of past unmanaged fire regimes. Fire hazard reduction includes logging operations that concentrate on the removal of saplings and pole-size trees and even some commercially valuable trees, but leave large mature trees. Stand densities should be reduced to levels observed before fire suppression. In undeveloped lands, stand-thinning can be accomplished with intense subcanopy broadcast burns, similar to those observed in the SSPM. If stands are too thick, slash removal of young and mid-size trees may be necessary before burning.

Fire management in Mexico

Until recently, a fundamental problem for fire management in Mexico has been the country's political centralization. Policy and budgetary decisions were made in Mexico City, with little flexibility for local and regional peculiarities or the development of unforeseen circumstances. The weather change in political administration brought about by the last presidential elections has opened the possibility for consideration of regional differences, and there are now several initiatives for the development of an integrated forest and fire management plan that would move away from the reactive policies of the past.

Nevertheless, a large proportion of Baja California's population immigrated recently from the tropics where the vegetation is not well adapted to fire. The immigrant's world view has not caught up with the reality of living in a mediterranean region. The public's negative perception of wildland fire that has been reinforced by the central communications media, and attitudes possibly appropriate for the tropics have been unquestioningly extended to Mexico's distant mediterranean corner.

Federal law requires that landowners be held responsible for wildland fires that start on their properties. All wildland fires detected by the authorities are reported to the Prosecutor for the Environment for possible prosecution. Determining responsibility is difficult since a large proportion of the territory is in common lands of *ejidos*, a communal form of landholding unique to Mexico. Prosecutors are reluctant to take on cases in which witnesses are lacking, where lightning was the likely cause of ignition, or where burning affected chaparral rather than riparian and mountain forests, which are viewed as inherently valuable. In actual practice, fewer than five percent of fires merit prosecution, most of these are cases that clearly involve malicious intent.

It has become evident that the fire suppression paradigm, which began to take effect in the 1960s in Baja California, is no longer accepted by the federal and state authorities, and most of the key managers agree that fire suppression is excessively dangerous and expensive for Mexican conditions. Few Baja California firefighters have sufficient training to understand the risks inherent in fighting wildland fire. When large fires do occur, only the military has sufficient manpower to mount a credible campaign, but putting untrained soldiers on the fire lines is potentially a prescription for disaster. Previous experience with wildland fire has shown that contracting aerial firefighting technology from the United States is a luxury that the treasury can ill afford. And it is widely recognized by the authorities that wildland fires go out naturally of their own accord, mostly due to factors beyond human control.

Forest resources, however, are almost universally seen as too valuable to allow to burn, and the public demands that “something” be done about forest fires. Thus, failure to “combat” forest fires is seen by the authorities as politically unacceptable. This dilemma has resulted in the persistence of the policy of fire suppression on the ground while at the same time there are official doubts as to its effectiveness. An operational compromise has developed which dictates mobilization against forest fires, but allows fires in shrublands to burn so long as there is little threat to lives or property. It is not generally recognized that this policy by default threatens the continued existence of Baja California’s small forests by repeating the mistakes made in the United States.

A complicating factor is that the detection and suppression of fires in the mountain forests of Baja California has long been a source of summer employment for several small brigades of firefighters whose job it is to detect and report fires in addition to “combating” them. Given the durability of this item in the Federal budget, it would be difficult now to wean the local population from this source of revenue. The role of the fire brigades should thus be amplified to include training and experience with prescribed fire. This would improve effectiveness by augmenting the firefighter’s experience and turn the brigades into a proactive force in reducing fuel loads in critical areas such as the environs of the National Astronomical Observatory.

Early indications are that the current presidential administration considers conservation of Baja California’s environment a priority, and it is likely that a nuanced approach to fire management will continue to be supported. An important opportunity for change may be provided by the initiative to reintroduce the California Condor to its former habitat in the Sierra San Pedro Mártir and its environs. This initiative, which is part of the effort to establish a biosphere reserve in the Sierra, would bring international attention to northern Baja California and require an extensive public relations campaign to acquaint the public with the importance of Baja California’s forest and shrubland habitat for the safe return of this emblematic bird. The reintroduction of the California Condor would present a good opportunity to educate Baja California’s public about the ecological realities of its environment while simultaneously developing the political credibility for a more realistic management of wildfire.

Conclusion

The very different dynamic in BCA stands in remarkable contrast with that on the California side. The BCA fire regime may serve as a model for SCA, prior to the establishment of modern suppression. Baja California's more natural fire regime and low labor costs provide an excellent opportunity for baseline research on fire and fuel management in Mediterranean-type regions. Given the public's reluctance to see valuable forest resources burn on public lands, reducing fuel loads manually, rather than allowing fire to do it, is widely seen as a viable option. Permitting the harvesting of fuels as an economic activity for local populations would be consistent with the "Mexican modality" for biosphere reserves. This would provide an opportunity to turn the Sierra San Pedro Mártir into a natural laboratory where different strategies of fire management could be tested side by side under nearly natural initial conditions.

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